Emulsion Cloud Chamber technique to measure the fragmentation of a high-energy carbon beam

S. Buontempo, G. De Lellis, F. Di Capua, A. Marotta, P. Migliozzi, Y. Petukhov*, C. Pistillo†, A. Russo, L. Scotto Lavina, P. Strolin, V. Tioukov[a] A. Ariga, N. Naganawa [b] T. Toshito [c] [d] Y. Furusawa[e] N. Yasuda[f]

[a]Dipartimento di Fisica, Università di Napoli & INFN Napoli, via Cintia, 80126 Napoli Italy

[b]Department of Physics, Nagoya University, Nagoya 464-8602, Japan

[c] CREST, Japan Science and Technology Agency, Kawaguchi 332-0012, Japan

[d]High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

[e]Research Center for Charged Particle Therapy, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan

[f]Fundamental Technology Center, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan

Beams of Carbon nuclei are now in use or planned to be used in various centers for cancer treatment around the world. The knowledge of the fragmentation of Carbon nuclei when they interact with the human body is important for evaluating of the spatial profile of their energy deposition in the tissues, hence the damage to tissues neighbouring the tumor. To this purpose, the identification of the fragmentation products is a key element. We present in this paper the charge measurement of about 3000 fragments produced by the interaction of ^{12}C nuclei with an energy of 400 MeV/nucleon in a detector simulating the density of the human body. The nuclear emulsion technique is used, by means of the so-called Emulsion Cloud Chamber. The nuclear emulsions are inspected using fast automated microscopes recently developed. A charge assignment efficiency of more than 99% is achieved. The separation of Hydrogen, Helium, Lithium, Berillium, Boron and Carbon can be achieved at two standard deviations or considerably more, according to the track length available for the measurement.

1. Introduction

Unlike the radiation conventionally used for cancer treatment, the particles called *hadrons* (such as protons) deposit most of their energy in a restricted domain around the end of their ionisation range. This leads to a high therapeutical effectiveness with minimal damage to neighbouring tissues. This is the merit of the so-called *Hadrontherapy*. The thickness traversed before depositing their energy can be tuned by changing the energy of the nuclei, typically of a few hundreds MeV/nucleon.

In 1967 it was pointed out [1] that, among hadrons, the use of nuclei is expected to improve the therapeutical effectiveness. Light nuclei and in particular Carbon nuclei are now used or planned to be used for cancer therapy in a number of dedicated facilities around the world [2].

The nuclear fragments generated in the interaction of the projectile nuclei inside the patient body go, however, beyond their ionisation range thus producing some damage in the tissues dowstream of the tumor [3,4]. The study of the fragmentation of the projectile nuclei is therefore important to ascertain and optimize the precision in hitting the tumor with minimal effects on the neighbouring tissues. Moreover, the data obtained in fragmentation studies contribute to de-

fine the parameters of nuclear interaction models entering in computer programs which simulate the biological effects for the optimization of their effectiveness.

Studies of the nuclear fragmentation are currently carried out using a target which, from the point of view of nuclear interactions, has properties close to those of the human body. The nuclear fragments are observed by detectors external to the target. Their identification was achieved by comparing the energy loss in a plastic scintillator and the total residual energy in a BGO scintillator [5,6]. The total charge-changing and partial cross-section of ^{12}C in carbon, paraffin and water was reported in Ref. [7] by using etched track detectors (Cr-39). Measurements of ^{10}B and heavier ions cross-section with several different targets were performed at GSI via the energy loss measurement in a large-area ionisation chamber [8].

Nuclear emulsions allow the measurement with very compact detectors of the fragments' emission angles event by event with granularity and space resolution at the micrometric level. The development of techniques of controlled fading of particle tracks [9] has opened the way to measurements of the specific ionisation over a very broad dynamic range. The possibility of identifying nuclear fragments through the measurement of their specific ionisation, linked to the fragment's electrical charge, has been demonstrated [10,11,12] by exposing an emulsion stack to beams of different nuclei. We choose nuclear emulsions as a detector for the study of the fragmentation of Carbon nuclei since they combine the characteristics of a very precise tracking device and the capability of measuring the charge through the ionisation.

The *Emulsion Cloud Chamber* (ECC) technique [13] consists in using a sequence of nuclear emulsion films interleaved with plates of passive material. It thus allows to integrate the target and the fragment detector. We have constructed an ECC with polycarbonate as passive material, approaching the nuclear properties of the human body. The ECC was exposed to a beam of ^{12}C nuclei with an energy of 400 MeV/nucleon. The ionisation of about 3000 nuclear fragments produced in their interactions in the ECC has been measured. In this paper we report on the fragment identification efficiency and on the purity obtained in this identification. The study of the fragmentation itself will be the subject of a forthcoming paper.

2. Nuclear emulsions

Nuclear emulsions [14] provide tracking of particle trajectories with a very high spatial resolution in the three dimensions, with the capability of measuring their ionisation. The passage of ionising particles produces a latent image which is turned into a sequence of silver *grains* (~ 0.6 μm diameter) after a complex chemical process known as development. The grains lie all along the trajectory of the particle which can thus be measured with a sub-micrometric accuracy.

The use of nuclear emulsions as a tridimensional tracking device for particle physics, more specifically for neutrino physics, was limited in the past by the lengthty scanning procedure, originally by visual inspection at the microscope. It has recently undergone a revival due to the impressive and rapid development of very fast automated scanning systems [15,16,17], with a scanning speed several orders of magnitudes higher than the first automated systems. A system devoted to very precise measurements was also developed [18]: the trajectory of tracks is measured with an accuracy of 0.06 μm in position and 0.4 mrad in angle, compared to about 2 mrad of systems oriented towards achieving the highest speed [15,16,17].

In nuclear emulsions, minimum ionising particles (MIPs) are observed as thin tracks with a grain density of about 30 grains/100 μm. The grain density in emulsion is almost proportional to the energy loss and its mean rate is given by the Bethe-Bloch equation [14].

The proportionality of the grain density to the energy loss by ionization holds over a limited range, above which a saturation effect dominates. This effect prevents the charge discrimination for high ionizing particles. Nevertheless, by keeping the emulsions for an appropriate time at a relatively high temperature (above 30° Celsius) and a high relative humidity (around 98%), a fading is induced which partially or totally erases the

tracks of particles [9]. Thus, for instance, films may be made unsensitive to MIPs and suited for highly ionising particles. This treatment is called *refreshing*. The combination of several films having undergone different refreshing treatments after exposure allows to disentangle particles with different charge and thus largely different ionization, overcoming saturation effects. This is the basis of the method reported in [10] and used for the present work.

The emulsions used for this work belong to the same batch of films used in the OPERA experiment for the study of neutrino oscillations [19]. The OPERA emulsion films [9] have been developed for large-scale, high precision experiments This development has allowed the first industrial production of nuclear emulsions (as for X-ray films), leading a considerably lower unit cost than previously possible though maintaining a sensitivity similar to that of handmade films. The OPERA nuclear emulsions have been produced by the Fuji company[3]. They consist of 44 μm thick emulsion layers deposited on both sides of a 205 μm thick plastic support. The surface size of the emulsion films is 12.5x10.0 cm^2.

3. The Emulsion Cloud Chamber and the beam exposure

We have built an ECC made of a sequence of nuclear emulsion films interleaved, as passive material, with 1 mm thick plates of polycarbonate (Lexan) in a multiple sandwich structure. The polycarbonate has a density of 1.15 g/cm^3 and an electron density of 3.6x10^{23} cm^{-3}. For comparison, the electron density of water (the main constituent of the human body) is 3.3x10^{23} cm^{-3} while the polymethil methacrylate target used in Ref. [5,6] has a density of 1.19 g/cm^3 and an electron density of 3.7x10^{23} cm^{-3}. Thus the target has similar characteristics to water for what concerns nuclear interactions.

The ECC consisted of 73 consecutive modules, each made of three emulsion films interleaved with polycarbonate plates. Its structure is shown in Fig. 1. The 3 emulsion films, denoted as R_0, R_1 and R_2, were treated differently after the exposure and before their chemical development. R_0 was not resfreshed and was developed soon after the exposure. R_1 and R_2 underwent a 3 day refreshing at 98% relative humidity with 30°C and 38°C temperature, respectively. The pile of emulsions and polycarbonate plates was vacuum packed. A light-tight aluminum tape was used to protect the pile from light.

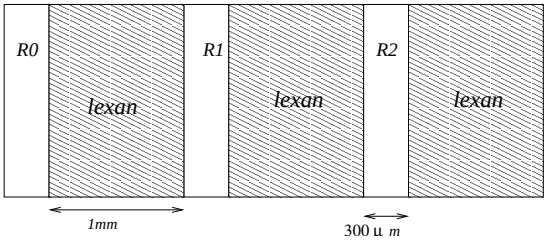

Figure 1. Structure of one of the 73 cells of the Emulsion Cloud Chamber. Each cell is made of 3 different emulsion films interleaved by Lexan sheets.

The ECC was exposed to a beam of ^{12}C nuclei with an energy of 400 MeV/nucleon at the Heavy Ion Medical Accelerator (HIMAC) in Chiba (Japan). The beam flux was monitored by a scintillator counter. On the emulsion films, an integrated flux of about 10 ^{12}C nuclei per mm^2 was obtained. This is a compromise between the need of a large statistics and the need of avoiding the overlapping between close vertices. The incident beam angle with respect to the emulsions and the polycarbonate plates had a spread of a few mrad. The ECC was placed in three position: with emulsion films perpendicular to the beam and inclined of about ±150 mrad. The tilted exposures were meant to improve the film to film alignment.

The chemical development was carried out at the Nagoya University. After the development, the films were brought to Naples University where they were analyzed by fast automated microscopes operating at a speed of 20 cm^2/hour with tracking efficiency larger than 90% and high purity ($\sim$ 2 fake tracks/cm^2) [16,17].

[3]Fuji Film, Minamiashigara, 250-0193, Japan.

4. Analysis methods

The automated microscopes have a focal depth of a few μm. Therefore, by varying the focal plane over 20 levels along the depth of the emulsion layers, they gather a series of tomographic images which are read by a CMOS camera. A track is seen as a sequence of grains at different depths, each grain consisting of a cluster of pixels. Apart from saturation effects, the grain density along the particle path is proportional to the specific ionization. Therefore as a variable sensitive to the specific ionization, hence to the particle charge, we take the sum of the pixels of all the grains belonging to the track normalized to a given track length in the emulsions. This sum is called *track volume*.

In the data acquisition, the automated microscope reconstructs the so-called *micro-tracks*, a micro-track being a sequences of aligned grains in a 44 μm emulsion layer. The alignment, within errors, of two micro-tracks in a film gives a so-called *base-track*. Base-tracks are characterised by a higher angular precision than micro-tracks, because of the lever arm given by the thickness of the plastic base and, for the grains close to the base, the absence of distortions resulting from the chemical development.

In the ECC, the emulsion films are piled up with a mechanical accuracy of a few hundred micrometers. By using straight penetrating tracks as references, in the offline analysis the films are aligned with an accuracy of a few micrometers [20]. After this fine alignment, base-tracks are associated to form *tracks* of particles.

In principle, each track is characterized by three track volume variables (VR_0, VR_1 and VR_2), one for each refreshing condition (R_0, R_1 and R_2) of the films traversed by the track. By averaging over the base-tracks in the emulsions having undergone the same refreshing, the statistical error on the track volume is reduced thus providing a better charge discrimination.

The R_2 refreshing procedure produces the complete erasing of all tracks of particle with charge equal to 1. Therefore, for proton identification only VR_0 and VR_1 are used. For Helium and heavier nuclei only VR_1 and VR_2 are effective, since VR_0 shows saturation. The charge separation is obtained by looking at correlations between appropriate pairs of track volume variables.

5. Results

In this analysis, all carbon interactions along the ECC are considered. This implies that the parent carbon energy ranges from almost 0 to 400 MeV/nucleon. Therefore also the fragmentation products have a very wide energy spectrum. In Fig. 2 we show the scatter plot of VR_0 versus VR_1 for the fragmentation products. We see two distinct peaks corresponding to H and He. Heavier ions are not clearly identified. By projecting the scatter plot onto an axis passing through the centers of the two peaks, we obtain the distribution of the variable VR_{01} shown in Fig. 3. A good separation between H and He is visible. The events in-between the two Gaussian distributions are due to the wide momentum distribution of the H produced by the carbon nuclei interactions.

Fig. 4 shows the scatter plot of VR_1 versus VR_2 for the fragmentation products. The separation of Helium, Lithium, Beryllium, Boron and Carbon becomes clear. By projecting the scatter plot onto an axis passing through the centers of the peaks, we obtain the distribution of the variable VR_{12} shown in Fig. 5. Also in this case, the fraction of events in-between He and Li is due to the low momentum tail of the He particles. The effect of the momentum spectrum becomes negligible for heavier nuclei since they tend to be produced with similar speed to the projectile.

Table 1 gives the separation of pairs of nuclei in standard deviations, for a set of different values of the number of base-tracks. The standard deviation σ for the separation of two nuclei is defined as $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$ where σ_1 and σ_2 are the standard deviations of the charge measurement for the two nuclei. In terms of total traversed ECC length, one base-track corresponds to 1.3 mm. One sees that to separate H-He, He-Li, Li-Be and Be-B at approximately 3 σ one needs 3, 5, 12 and 30 base-tracks, respectively. With 30 base-tracks, Boron and Carbon have a 2.4 σ separation. With sufficient track lengths, even better separations are achieved.

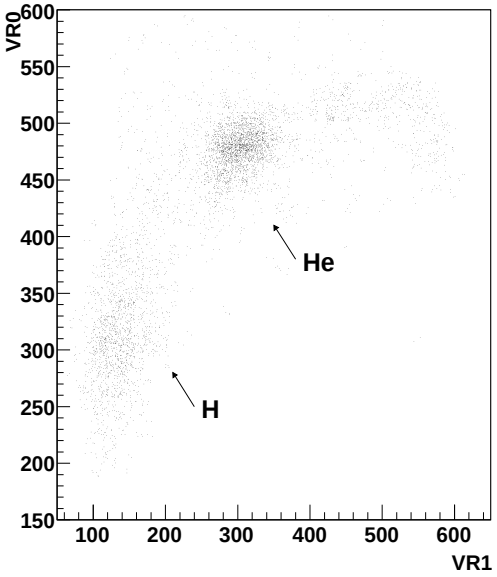

Figure 2. Scatter plot of VR_0 versus VR_1, providing the separation of H from He and heavier nuclei.

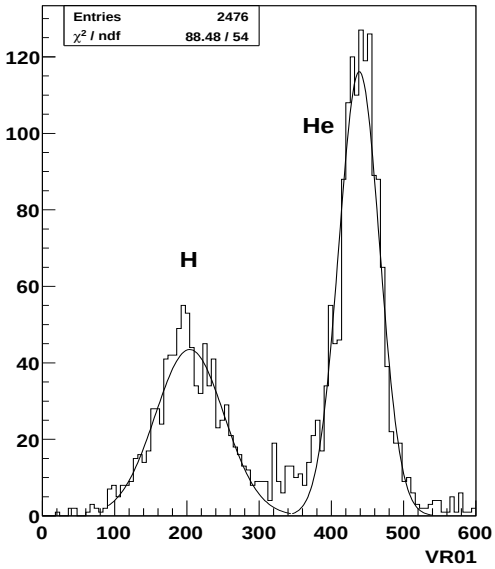

Figure 3. The distribution of VR_{01}, providing the H and He separation. The tracks originate from the fragmentation of carbon nuclei all along the chamber.

We have collected and analyzed about 3000 tracks. The charge assignment failed only for 27 of them. The corresponding charge assignment efficiency is $(99.1 \pm 0.2)\%$. The inefficiency is connected to very short tracks. Indeed, the 27 tracks are tracks with only 2 base-tracks, in R_0 and R_2, thus preventing the estimate of both the variables VR_{01} and VR_{12}.

6. Conclusions

We have exposed an Emulsion Cloud Chamber to a beam of ^{12}C nuclei with an energy of 400 MeV/nucleon. The chamber was made of nuclear emulsion films and polycarbonate plates. We have analyzed about 3000 particle tracks produced by the Carbon fragmentation inside the chamber. By analyzing the grain density along the particle track by means of fast automated microscopes, we were able to assign the charge to these fragments with 99% efficiency. The charge separation improves statistically with the track length. The separation of the Hydrogen, Helium, Lithium, Berillium, Boron and Carbon can be achieved at two standard deviations or considerably more, depending on the track length which is used for the measurement.

Acknowledgments

We thank Prof. M. Durante for several suggestions and comments to the manuscript. We also thank Prof. K. Niwa and Prof. G. Gialanella for useful discussions and support. The Italian Ministry for University and Research (MUR) funded this work within the PRIN2004 projects. We acknowledge the Istituto Nazionale di Fisica Nucleare for the equipment used. In Japan, this work was performed as a Research Project with Heavy

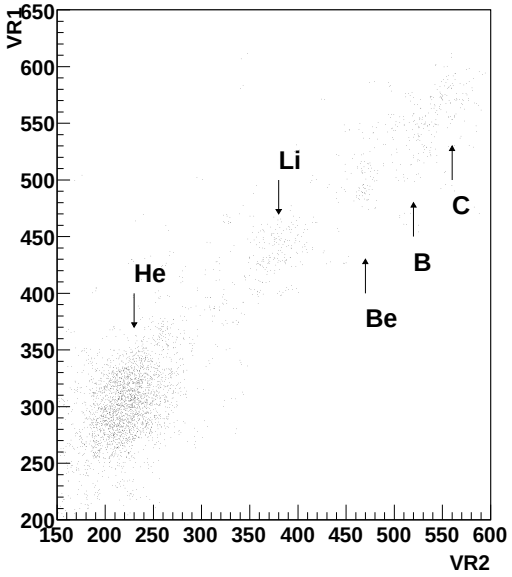

Figure 4. Scatter plot of VR_1 versus VR_2. This provides the separation between He and heavier ions.

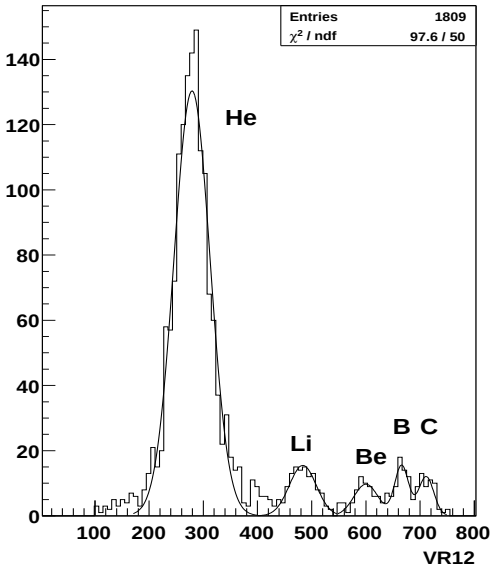

Figure 5. The distribution of VR_{12}, showing the separation between He, Li, Be, B and C. The tracks originate from the fragmentation of carbon nuclei all along the chamber.

Ions at NIRS-HIMAC. We express our gratitude to the HIMAC laboratory and to its staff for assistance.

REFERENCES

1. C.A. Tobias and P.W. Todd et al., Heavy charged particles in cancer therapy, *Natl Cancer Inst. Monogr.* **24** (1967) 1.
2. Particles, *Newsletter by the Particle Therapy Co-Operative Group (PTCOG)*, **32** (2003) 474
3. H.D. Maccabee and M.A. Ritter, Fragmentation of high-energy oxygen-ion beams in water, *Radiat. Res.* **60** (1974) 409.
4. W. Schimmerling, S.B. Curtis and K.G. Vosburg, Velocity spectrometry of 3.5 GeV nitrogen ions, *Radiat. Res.* **72** (1977) 1.
5. N. Matsufuji et al., Influence of fragment reaction of relativistic heavy charged particles on heavy-ion radiotherapy, *Phys. Med. Biol.* **48** (2003) 1605.
6. N. Matsufuji et al., Spatial fragment distribution from therapeutic pencil-like carbon beam in water, *Phys. Med. Biol.* **50** (2005) 3393.
7. A. N. Golovchenko et al., Total charge-changing and partial cross-section measurements in reactions of ∼100-250 MeV/nucleon ^{12}C in carbon, paraffin and water, Physical Review **C66** (2002) 014609.
8. I. Schall et al., Charge-changing nuclear reactions of relativistic light-ion beams ($5 \leq Z \leq 10$) passing through thick absorbers, Nucl. Instrum. Meth. **B117** (1996) 221.
9. T. Nakamura et al., The OPERA film: new nuclear emulsion for large-scale, high precision experiments. *Nucl. Instrum. Methods* **A556** (2006) 80.
10. T. Toshito et al., Charge identification of

Table 1
The separation of pairs of nuclei in standard deviations, for a set of values of the number of base-tracks. Standard deviations are defined in the text.

Base-tracks	3	9	13	20	30
H-He	3.3	4.5	6.5		
He-Li	2.6	3.9	4.3	5.0	
Li-Be	1.7	2.7	3.1	3.5	4.1
Be-B			2.0	2.5	2.8
B-C				1.9	2.4

highly ionizing particles in desensitized nuclear emulsion using high speed read-out system *Nucl. Instrum. Methods* **A556** (2006) 482.

11. T. Toshito et al., Study on the applications of emulsion technology for the purpose of astrophysics and medicine, Proceeding of the 4th Japan-Korea Joint Meeting on Medical Physics, Japanese Journal of Medical Physics Vol.25 Supplement No.3-1 September 2005, 401-403.
12. T. Toshito, Study on Nuclear Fragmentation by High Speed Emulsion Read-Out System, IEEE 2006 Nuclear Science Symposium, Medical Imaging Conference and 15^{th} International Room Temperature Semiconductor Detector Workshop, October 2006 San Diego, California. Conference Record N23-6.
13. M. Kaplon, B. Peters and D.M. Ritson, Emulsion Cloud Chamber study of a high energy interaction in the cosmic radiation, *Phys. Rev.* **85** (1952) 900.
14. C.F. Powell, P.H. Fowler, D.H. Perkins, *The Study of Elementary particles by the Photographic Method*, Pergamon Press, Oxford, 1959;
    W.H. Barkas, *Nuclear Research Emulsions*, Academic Press, New York, 1963.
15. S. Aoki et al., The fully automate emulsion analysis system, *Nucl. Instrum. Methods* **B51** (1990) 466;
    T. Nakano, BUTSURI 56 (2001) 411 (in Japanese)
16. N. Armenise et al., High-speed particle tracking in nuclear emulsion by last-generation automatic microscopes, *Nucl. Instrum. Methods* **A551** (2005) 261;
17. L. Arrabito et al., Hardware performance of a scanning system for high speed analysis of nuclear emulsions, *Nucl. Instrum. Methods* **A568** (2006) 578.
18. M. De Serio et al., High precision measurements with nuclear emulsions using fast automated microscopes, *Nucl. Instrum. Methods* **A554** (2005) 24.
19. R. Acquafredda et al., First events from the CNGS neutrino beam detected in the OPERA experiment, New J.Phys. **8** (2006) 303.
20. L. Arrabito et al., Track reconstruction in the emulsion-lead target of the OPERA experiment using the ESS microscope, to be submitted to Journal of Instrumentation.